NISTIR 6327

Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

Report from the NIST/ACI/ASTM Workshop held in Gaithersburg, MD on November 9-10, 1998

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United States Department of Commerce
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Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Ray Kammer, *Director*

ABSTRACT

The NIST / ACI / ASTM workshop on "Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete" was focused on possibilities for developing and standardizing such models, specifically for chloride-exposed concrete. The report includes summaries of nine presentations by model developers and reports from working groups that addressed i) chloride transport mechanisms and test methods, ii) chloride thresholds for corrosion initiation, iii) corrosion rate and time to rehabilitate or replace, and iv) life-cycle cost and service life prediction models. Several models for chloride transport to the steel were well advanced, but modelling of chloride thresholds and corrosion rates poses difficulties that still need to be overcome. Economic models for life-cycle costing are in place and ready to use with service life models as they are developed. It was agreed that standard models for service life prediction and life-cycle costing are necessary . It was recommended that a simple, but useful model could and should be developed and standardized in the short term, with a more scientifically sound model being a longer term objective. The model development would need to be supported by development of some new standard test methods and databases containing appropriate and reliable data. Standardization of the models would be expected to be carried out in ACI committees and standardization of test methods in ASTM. NIST's Partnership for High-Performance Concrete Technology would contribute to the development of models, test methods, and data.

Keywords: Chlorides; concrete; corrosion; corrosion threshold; economics; models; reinforcement; service life; transport processes.

ACKNOWLEDGMENTS

The success of the workshop described in this report was due to the collective efforts of many persons. We wish to thank the following for their contributions:

- The Steering Committee for deciding on the workshop objectives, the workshop structure, and the list of invitees;
- The invited speakers for providing essential background information and a perspective for the working group discussions;
- The chairs, co-chairs and recorders for giving direction to the discussions and ensuring that the main ideas were captured;
- All the participants for providing the viewpoints that the workshop was set up to obtain; and
- NIST staff members Nancy Wilkin and Romayne Hines for the excellence of the arrangements, and for providing friendly help wherever it was needed during the workshop.

We are grateful to the sponsoring organizations, the American Concrete Institute and the American Society for Testing and Materials, for lending their support to the workshop.

Special thanks and appreciation are due to the W.R. Grace and Master Builders companies for sharing in expenses for the workshop, including underwriting the costs of refreshments and the workshop dinner.

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EXECUTIVE SUMMARY

A workshop cosponsored by ACI, ASTM and NIST was held in Gaithersburg, Maryland, on November 9-10, 1998. The subject was "Modelling Service Life and Life-Cycle Cost of Steel-Reinforced Concrete." The workshop resulted from a discussion within the Strategic Development Council of ACI in May 1998 concerning the need for standards for the subject of the workshop.

The workshop objectives were:

1. To review current models for determining the service life and life-cycle cost of steel-reinforced concrete subjected to chloride-induced corrosion of the steel:
2. To reach agreement on an approach to development of a comprehensive model that would provide a suitable basis for standardization;
3. To identify new data and test methods, if any, needed to support development of the model; and
4. To recommend actions to be taken to develop the model and propose it for standardization.

The workshop began with ten invited presentations, several from experts from other countries, that provided an overview of current modelling activities. The first presentation reviewed the purpose and activities of the RILEM Technical Committee TMC, Modelling Chloride Penetration in Concrete, and the later presentations described service life models developed in Canada (2), Denmark (1), Sweden (1), and the United States (4), and life-cycle cost models developed in the United States (2). The service life models were all based on calculations of time to initiation of corrosion of the reinforcing steel.

The invited presentations were followed by two breakout sessions in each of which four working groups discussed assigned topics. In the first session, all four groups addressed the question, "How could a framework for development of a standard, or standards, for service life and life-cycle cost of chloride-exposed, steel-reinforced concrete best be developed?" In the second session, each group had a different assignment, the four assignments being 1) chloride transport mechanisms and test methods, 2) chloride thresholds for corrosion initiation, 3) corrosion rate and time to rehabilitate or replace, and 4) service life prediction and life-cycle costing.

Among the results from the first four working group discussions were agreement that there was an urgent need for service life and life-cycle cost models for chloride-exposed, steel-reinforced concrete and that the model or models developed immediately on the basis of current knowledge should be followed by development over the long term of a more comprehensive model reflecting sound scientific knowledge of the corrosion process. Suggested criteria to be met by a model to meet the immediate need were that it should:

- Be verifiable by comparison of its outputs with actual data, e.g., the model should be able to make accurate predictions of chloride contents
- Be well-documented and have background material clearly presented, with assumptions and limitations being clearly stated

- Offer help on input values
- Have a statistical basis for assumptions (with respect to input values, diffusion coefficients (d_a), surface concentrations, and environment)
- Have the smallest possible number of adjustable coefficients
- Deal with as many known mechanisms as practical
- Provide data for economic analysis

The more comprehensive "scientific" model to be developed over the longer term should:

- Meet all the criteria for the immediate model
- Incorporate lesser-known transport mechanisms
- Incorporate multiple deterioration mechanisms
- Correlate service conditions and microclimates
- Link microclimate to macroclimate
- Include preventive maintenance
- Include corrosion propagation.

It was pointed out that a database incorporating appropriate and reliable data will be needed to support model development. The data is needed for determination of apparent diffusion coefficients, for testing and verification of existing models, and the selection of one or more models for further development. The database should include surface chloride concentrations and chloride contents for at least five different locations (depths), mixture designs, age (at least up to ten years), and temperature. It was emphasized that if the mixture proportions were not recorded, other data would be of little value.

<u>Chloride transport mechanisms and test methods</u>

In the second breakout session, the group discussing chloride transport mechanisms and test methods emphasized the need for good sampling if good data is to be obtained from the field. Guidelines on sampling are needed and as a minimum, they should cover coring, profiling, and analytical procedures, with the sampling being appropriate to the situation. Examples of different situations are a bridge deck, a sea wall, and a tunnel wall. Many factors must be considered in studies of transport mechanisms including: i) binding of chloride, ii) age dependance, iii) temperature dependance, iv) surface barriers, and v) cracks, with diffusion, convection and unsaturated flow being transport mechanisms that must all be addressed.

<u>Chloride thresholds for corrosion initiation</u>

The working group on chloride thresholds for corrosion initiation pointed out the need for an accepted, mechanism-free definition of the "corrosion threshold." It recommended that the definition should be:

> *The chloride threshold, C_T, is the mass of total chloride per unit volume of concrete that results in permanent depassivation of the steel (for a specific set of mixture proportions, history, and environmental factors).*

It also recommended that there be consistency in the units used for expressing the chloride threshold. The most reliable method for determination of the threshold is that based on field survey data. Results from slow ingress of chloride into concrete (usually over several years) is useful but not as reliable and, unfortunately, results obtained from immersion of the steel in simulated concrete pore solution, while easiest to obtain, do not correlate well with data from field surveys. Chloride thresholds appear to depend on many factors including: chloride concentration, concrete ingredients (type and source of aggregate, type of pozzolan, type of cement, and types of chemical admixtures), mixture proportions, consolidation (voids, settlement around the rebar, interfacial porosity), finish and cure, local environment (temperature, moisture content, oxygen, pH, CO_2, solutes, and chloride source), electrical potential, time, the reinforcing metal, and the intrinsic variability of concrete.

Corrosion rates and time to rehabilitate or replace

The working group addressing corrosion rates and time to rehabilitate or replace believed that modelling of corrosion rates should be possible, though more data is needed to support the model development. Data, such as on the mechanical properties of rust, is needed for modelling relationships between corrosion rate, stress in rust, and stress in concrete. The problem is complex and its solution will require a fracture mechanics approach. Another need is for methods for characterizing damage levels, since those that now exist only account indirectly for the factors that determine the need to repair. The FHWA rating system should be used as a starting point. It must be recognized that different steels are different in their susceptibilities to chloride-induced corrosion, and knowledge is needed on the effects on corrosion rate of factors such as mill scale, cracks, and crevice corrosion. Modelling the corrosion of epoxy-coated rebars will involve localized corrosion, and agreement should be sought on damage functions for epoxy-coated bars and for systems containing corrosion inhibitors. Data is needed on such systems to help evaluate damage in them. Regarding existing models, they do not address all critical aspects of time to failure; for example, few, if any, cover corrosion rates. A question that must be asked is, What constitutes failure and how can it be modelled? Is it failure of the bond and deterioration of the concrete? Or loss of tensile capacity due to the reduced cross-section of the steel? For modelling purposes it will be necessary to separate new construction from repair, with verification of information taking place during the design phase.

Service life prediction and life-cycle cost

The working group on service life prediction and life-cycle cost concluded that there is enough information to be able to make a stab at producing a useful model and for life-cycle cost modelling, the methodology is already in place in ASTM E917. In the short term, models may have to include 'fudge factors" but, for the long term, a comprehensive service life model should be the goal; among the requirements for such a model is that the corrosion initiation portion should have a probabilistic base. A task group should be set up to allow public input to the model development and standardization. Within the task group, there should be working groups on a) "empirical" modelling of transport, b) "scientific" modelling of transport, c) the corrosion threshold (models and test methods), and d) life-cycle cost. There will be several barriers -- some technical, some institutional -- to overcome in developing and gaining acceptance for the desired models. Among them will be code committee members who will not be comfortable with inclusion of diffusion coefficients in concrete codes, and the current lack of standard test methods needed to develop a common database. For the most rapid progress, different organizations should each play a part. Test methods and specifications would be expected to be addressed in ASTM and CEN, with guides and codes being addressed by ACI and RILEM. Momentum built at the present workshop should be maintained through a continuing series of workshops.

Recommendations

Following the breakout sessions, a final plenary session heard reports from the working groups and ended with a general discussion leading to several key recommendations.

The key recommendations from the workshop were:

1. A subcommittee on modeling of service life and life-cycle cost of reinforced concrete should be established in ACI Committee 365, Service Life Prediction. The subcommittee should establish guidelines for the models and, using the current state of knowledge, develop a baseline corrosion service life and life-cycle cost model as rapidly as possible.
2. The baseline model should be made available to the industry for testing and implementation and then placed on the Web, possibly with a list of other models and links to them. The possibility of forming an on-line discussion group should be considered.
3. Over a longer term, a comprehensive model based on scientific understanding should be developed through the joint activities of an industry-government consortium and the relevant standards organizations. Test method standards should be developed in ASTM Committee C09, Concrete and Concrete Aggregates, and ASTM Committee G01, Corrosion.
4. An organization such as NIST should be given responsibility for maintaining the model on the Web and for making necessary updates as further developments occurred.

Conclusion

In response to the first recommendation, a subcommittee was set up in ACI Committee 365, Service Life Prediction, with the purpose of carrying out the recommendations. Michael Thomas of the University of Toronto was invited to become chairman of the new subcommittee and he accepted the appointment.

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
CEN	European Standards Organization
CIKS	Computer-integrated knowledge system
CGI	Common Gateway Interface
CSE	Copper sulfate electrode
CTH	Chalmers University of Technology
FHWA	Federal Highway Administration
HPC	High-performance concrete
ISO	International Organization for Standards
NDE	Non-destructive evaluation
NT	Nordic Test
OPC	Ordinary portland cement
RCPT	Rapid chloride penetration test
RILEM	International Union of Research and Testing Laboratories for Materials and Structures
SHRP	Strategic Highway Research Program
SI	International System of Units
WG	Working Group

APPENDIX 1

Steering Committee and Workshop Participants

Steering Committee

Geoff Frohnsdorff	Building and Fire Research Laboratory, NIST
Shuaib Ahmad	American Concrete Institute
Emmanuel Attiogbe	Master Builders, Inc.
Neal Berke	W.R. Grace Company
Dan Falconer	American Concrete Institute
Doug Hooton	University of Toronto
Paul Johal	Prestressed/Precast Concrete Institute
Colin Lobo	National Ready Mixed Concrete Association

Workshop Participants

Shuaib Ahmad	American Concrete Institute
Antonio Aldekiewicz	W.R. Grace Company
Stephen Amey	Master Builders Inc.
Emmanuel Attiogbe	Master Builders Inc.
Dale Bentz	Building and Fire Research Laboratory, NIST
Evan Bentz	University of Toronto, Canada
Neal Berke	W.R. Grace Company
Nick Carino	Building and Fire Research Laboratory, NIST
Marta Castellote	Eduardo Torroja Inst. of Construction Sciences, Spain
Jim Clifton	Building and Fire Research Laboratory, NIST
Mark Ehlen	Building and Fire Research Laboratory, NIST
Geoff Frohnsdorff	Building and Fire Research Laboratory, NIST
Ed Garboczi	Building and Fire Research Laboratory, NIST
David Gustafson	Concrete Reinforcing Steel Institute
Terry Holland	Silica Fume Association; and Chairman, ACI / TAC

Workshop Participants (continued)

Doug Hooton	U. of Toronto, Canada
Paul Johal	Precast/Prestressed Concrete Institute
Paul Kelley	Simpson, Gumpertz and Heger
Alistair MacDonald	W.R. Grace Company
Bryan Magee	Purdue University
Jaques Marchand	Laval University, Canada
Nick Martys	Building and Fire Research Laboratory, NIST
Matthew Miltenberger	Master Builders Inc.
George Muste	National Ready Mixed Concrete Association
Ted Neff	Consultant
Lars-Olaf Nilsson	Chalmers University, Sweden
Charles Nmai	Master Builders Inc.
Jan Olek	Purdue University
Ed O'Neil	U.S. Army Corps of Engineers / WES
Michael Ortlieb	Carl Walker, Inc.
Clauss Germann Petersen	Germann Instruments, Denmark
Mark Postma	Carl Walker, Inc.
Ervin Poulsen	AEC, Denmark
Alberto Sagüés	South Florida University
Michael Sprinkel	Virginia Transportation Research Council
Michael Thomas	University of Toronto, Canada
Paul Tourney	Grace Construction Products
David Trejo	University of Texas
Alex Vaysburd	Structural Preservation Systems
Paul Virmani	Federal Highway Administration

APPENDIX 2

THE NIST / ACI / ASTM WORKSHOP ON MODELS FOR PREDICTING THE SERVICE LIFE AND LIFE-CYCLE COST OF STEEL-REINFORCED CONCRETE

AGENDA

DAY 1 (November 9)

7:30 Continental Breakfast

Plenary Session 1

8:00 Welcome and review of the workshop goals — Geoffrey Frohnsdorff, BFRL/NIST

RILEM Technical Committee TMC, Testing and Modelling Chloride Penetration in Concrete – Goals and Plans

8:10 Marta Castellote, Eduardo Torroja Institute of Construction Sciences, Spain

Presentations on Models for Predicting Service Life and Life-Cycle Cost of Steel-Reinforced Concrete

8:40 Alberto Sagues, University of South Florida

9:10 Lars-Olof Nilsson, Chalmers University, Sweden

9:40 Ervin Poulsen, AEC, Denmark

10:10 COFFEE BREAK

10:25 Michael Thomas, University of Toronto, Canada

10:55 Jacques Marchand, Laval University, Canada

11:25 Paul Tourney, W.R. Grace Company

11:55 Matthew Miltenberger, MasterBuilders Company

12:25 BUFFET LUNCH

1:25 Dale Bentz, Building Materials Division, BFRL/NIST

1:55 Mark Ehlen, Office of Applied Economics, BFRL/NIST

Working Group Activities

2:25 Instructions to Working Groups

2:40 BREAK

Working Group Session 1

3:00 Working Group discussions (WG 1 through WG 4)

5:30 Adjournment

6:30 DINNER

8:00 Meeting of Steering Committee with Working Group Chairs/Co-Chairs

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<u>**DAY 2**</u> **(November 10, 1998)**

7:30 Continental Breakfast

Plenary Session 2

8:00 Reports from chairs of WGs in Working Group Session 1

Working Group Session 2

9:00 Working Group discussions (WG 5 through 8)

10:30 COFFEE AVAILABLE

12:00 BUFFET LUNCH

Plenary Session 3

12:45	Reports from chairs of WGs in Working Group Session 2	Terry Holland, Consultant
2:40	Final discussion and recommendations for action	Terry Holland, Consultant
3:00	Adjournment	

APPENDIX 3

Working Group Assignments

Working Group 1

Doug Hooton, Chair
Shuaib Ahmad, Co-Chair
Nick Martys, Recorder
Mark Ehlen
Terry Holland
Alistair MacDonald
Jacques Marchand
Lars-Olof Nilsson
Charles Nmai
Ervin Poulsen

Working Group 2

Albert Sagues, Chair
Neal Berke, Co-Chair
Dale Bentz, Recorder
Stephen Amey
Evan Bentz
Paul Kelley
George Muste
Michael Ortlieb
Mike Sprinkel
David Trejo

Working Group 3

Jan Olek, Chair
Paul Johal, Co-Chair
Ed Garboczi, Recorder
Marta Castellote
Geoff Frohnsdorff
Matthew Miltenberger
Clauss Germann Petersen
Mark Postma
Paul Tourney
Alex Vaysburd

Working Group 4

Mike Thomas, Chair
Emmanuel Attiogbe, Co-Chair
Nick Carino, Recorder
Anthony Aldykiewicz
James Clifton
Dave Gustafson
Bryan Magee
Ted Neff
Ed O'Neill
Paul Virmani

Working Group Assignments (continued)

Working Group 5

Doug Hooton, Chair

Shuaib Ahmad, Co-Chair

Nick Martys, Recorder

James Clifton

Paul Kelley

Alistair MacDonald

Matthew Miltenberger

Ted Neff

Lars-Olof Nilsson

Clauss Germann Petersen

David Trejo

Working Group 6

Alberto Sagues, Chair

Neal Berke, Co-Chair

Dale Bentz, Recorder

Marta Casellote

Geoff Frohnsdorff

Bryan Magee

Charles Nmai

Mark Postma

Alex Vaysburd

Working Group 7

Jan Olek, Chair

Paul Johal, Co-Chair

Ed Garboczi, Recorder

Anthony Aldykiewicz

Stephen Amey

Dave Gustafson

Jacques Marchand

Ed O'Neill

Ervin Poulsen

Paul Virmani

Working Group 8

Mike Thomas, Chair

Emmanuel Attiogbe, Co-Chair

Nick Carino, Recorder

Evan Bentz

Mark Ehlen

Terry Holland

George Muste

Michael Ortlieb

Mike Sprinkel

Paul Tourney

APPENDIX 4

New, Formable, Corrosion-Improved, Low-Carbon Steels for Concrete

(An abstract provided by Gareth Thomas, University of California, Berkeley and San Diego, who was unable to attend the workshop)

Reinforced concrete structures are an integral part of everyday life. Inadequacies in the overall design perspectives of reinforced concrete structures, which pay insufficient attention to durability – mainly corrosion resistance – result in many structures deteriorating well before their life expectancy. The result is enormous costs for repair and rehabilitation of highway structures due to corrosion damage, amounting to billions of dollars.

An important challenge is to involve the principles of Materials Science and Engineering, to design by microstructural control, through processing, steels which are economically attractive, and which provide superior mechanical and corrosion resistance properties. This paper describes such an approach using the principles of low carbon dual phase steel (DFM).

In this system, the microstructure is designed to avoid carbide particles which in the presence of ferrite, or other phases, localizes the anodic-cathodic coupling in a galvanic situation. Since all structural steels in current use have carbides in their structure, they are all susceptible to galvanic attack. Thus, the design of steels with ferrite-martensite structures (DFM), in the absence of carbides, allows us to easily attain mechanical property requirements for reinforcements, with greatly improved corrosion resistance.

In all cases, the DFM steels show superior properties, are easily welded and show excellent formability, e.g., in wire drawing, corrosion results show that in the long-term weight loss data, a smooth bar showed no detectable corrosion after one year, and the short-term tests in chloride solutions, dramatically shows the superior corrosion resistance of DFM to A-615 rebars; the latter are almost completely destroyed after three weeks exposure.

- The original paper, by Gareth Thomas of the University of California and David Trejo of Michigan State University, was presented at the Workshop on Materials for the Infrastructure, La Jolla, California, April 1-3, 1998. The workshop was sponsored by the Institute for Mechanics and Materials (IMM), University of California, San Diego (UCSD), and the National Science Foundation. The workshop proceedings were published as Report No. 98-1 from the IMM, UCSD, 9500 Gilman drive, Dept. 0404, La Jolla, CA, 92093-0404.

APPENDIX 5

Loading Effect on Corrosion of Reinforcing Steel

(Abstract provided by Surendra Shah of Northwestern University who was unable to attend the workshop)

A great deal of research on corrosion of reinforcing steel in concrete has been done regarding material properties, mix proportions, corrosion protection, repair and retrofitting, as well as service life prediction. Limited work has been done clearly illustrating the mutual interaction among loading, cracking, and corrosion damage. The objective of the present research is to investigate this interaction. Reinforced concrete beams, (10 x 10 x 110) cm, were prepared and subjected to different levels of flexural loading: (0, 45, 60, and 75) % of the ultimate load. They were also exposed to a laboratory environment with ponding and wetting / drying cycling at room temperature. Half cell potential and galvanic current measurements were taken daily to monitor the corrosion of the reinforcing steel. After corrosion initiation, external current was applied to the beams to accelerate the corrosion. The beam deflections and crack characteristics were recorded during the entire test. The remaining loading capacity of the beams was evaluated at the end of the experiment. The results indicate that loading has a significant effect on the corrosion rate of reinforcing steel. Corrosion increases beam deflection. Loading level has a considerable effect on the initiation of corrosion, but the effect reduces after corrosion initiation. The beams under load had much higher corrosion rates than those which had been preloaded and then unloaded. The present research may provide another look into current service life predictions of concrete.

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* The abstract was of a paper submitted to the ACI Spring Convention in Chicago in March 1999. The authors are Sang-chun Yoon, Hyung-rae Kim, Kejin Wang, Jason Weiss, and Surendra P. Shah, NSF Center for Advanced Cement-Based Materials, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208.

APPENDIX 6

Chloride Penetration into Concrete with Light Weight Aggregates

(Abstract provided by Magne Maage of Selmer ASA, Trondheim, who was unable to attend the workshop) *

The experimental work started as a part of the Lightcon project with the objective of studying chloride ingress into practical LWA concretes depending on many variables as well as giving input to the model for service life prediction developed in the same project. Eight concretes have been tested, two by two were identical except that half of the cement content was replaced by slag in one of the two. All mixes had 5 % to 10 % silica fume by weight of cement plus slag. The most important variables were: (1) curing time before exposure, (2) curing time (20, 65 and 95) °C, (3) exposure temperature (5, 20 and 35) °C, (4) exposure time, (5) type of exposure (submerged, splash, spray), (6) salt concentration in exposure water (1, 4 and 10) %, (7) type of binder (OPC and OPC + slag).

The most important conclusion was that the results fitted very well to the hypothesis for service life prediction. Additionally, the following main conclusions may be mentioned:

Surface chloride content, C_s , is the environmental load and it increases with exposure time during the first years, reduces with increased curing time and introduction of slag, and independent / inconsistent correlation to curing and exposure temperature.

The achieved diffusion coefficient, D_s , is independent of curing and exposure temperature, decreases with exposure time and introduction of slag.

The parameter, α , expresses the time dependency of D_i with exposure time; a is independent of curing time, curing and exposure temperature, and increase somewhat with increased salt concentration in the exposure water and introduction of slag.

* This abstract is from a draft report by M. Maage, S. Helland, and J.E. Carlsen, Chloride Penetration into Concrete with Light Weight Aggregates, Report 3.X, SINTEF, Trondheim, Norway, scheduled for publication at the end of 1998.